Far Infrared interferometer technology development: a progress report

M. R. Swain[a], P. J. Dumont[a], P. R. Lawson [a], J. D. Moore[a], R. F. Smythe[a], C. K. Walker [b], and C. Y. Drouet d'Aubigny[b]

[a]Jet Propulsion Laboratory, 4800 Oak Grove Dr., MS 171-113, Pasadena, CA, 91109 USA
[b]Steward Observatory, University of Arizona, 933 North Cherry Ave, Tucson, AZ, 85721 USA

ABSTRACT

We report on the progress of developing a cryogenic delay line and integrated optics components. These are some of the critical components needed to enable farIR, direct detection, interferometers. To achieve background limited performance in the 40 to 400 μm region, the interferometer optics and delay line must be cooled to near liquid Helium temperatures. The cryogenic delay line design incorporates a number of novel features and has been tested and characterized at liquid nitrogen temperatures. The integrated optics effort has focused on producing single mode spatial filters and beam combiners.

Keywords: Interferometer, infrared, cryogenics, integrated optics

1. INTRODUCTION

To achieve background-limited sensitivity in space (sky shot noise limited), far-infrared instruments require low-noise detectors and cryogenic optics. This requirement for the optics adds an additional challenge for interferometry because of the added complexity of cryogenic delay lines and beam combining optics. The thrust of our effort is to develop far-infrared interferometer enabling technologies; presently our focus is on cryogenic delay lines and on integrated optics for beam combination.

2. CRYOGENIC DELAY LINES

An ideal delay line should provide smooth, predictable, controllable motion in one degree of freedom while remaining rigid in the other five degrees of freedom. An approximation of this ideal is challenging warm and is even more difficult at cryogenic temperatures. Because of our concerns about the ability of bearings to operate very smoothly at cryogenic temperatures for long periods of time, we have concentrated on delay line designs which do not use axles. For the far infrared, we anticipate delay line operation at temperatures as low as 4 Kelvin.

We have focused our efforts on delay line designs which provide up to a half meter of optical delay. The two basic concepts we are exploring to make a scanning stage are a "strapped wheel" design and a "flex-blade" design. For a given size of delay line, the strapped wheel design has more travel but is less rigid than the flex-blade design. This make the strapped wheel designs more attractive for long wavelength applications (eg. 100 μm spatial interferometry) and the flex-blade design more attractive for high precision applications (eg. 10 μm high precision nulling).

The strapped wheel delay line provides linear motion of an optical stage by rolling on wheels with respect to a fixed stage ([1]). The wheels are strapped to the stages to guide the wheel path (Figure 1). The straps are tensioned with a flexure-based preload. One each side, the wheels are strapped together to react the preload force in wheel to wheel strap tension. The upper and lower stages are held together with a magnetic preload. The magnets, held in counter bores in the fixed stage, pull on a steel bars held in close proximity and mounted to the optics stage. The optics stage is translated using a stepper motor working against a spring preload.

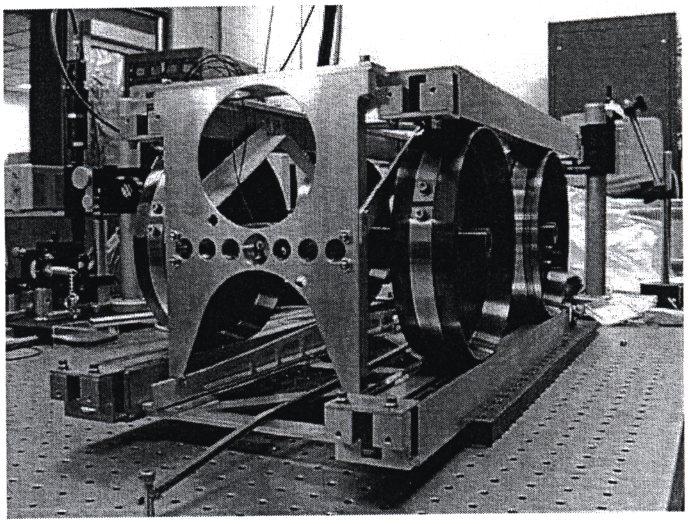

Figure 1.
The strapped-wheel delay line stage with out optics. In operation, the optics are suspended from the upper stage. Alignment of scanning stage is controlled by adjusting the wheel strap preload on individual wheels. This delay has 25 cm of physical travel and has operated at $\sim$ 100 Kelvin.

Alignment consists of adjusting the individual wheel strap preload to minimize the lateral run-out (which would translate into beam shear) of the optical stage.

The flex-blade delay line is based on a nested pair of parallel motion flexures arranged so that inner stage cancels the shear caused by the outer stage during translation (Figure 2). This requires the inner stage and outer stages be synchronized and that the inner stage translate twice as far as the outer stage. Our design uses a single stepper motor driving the inner and outer stages via a stepped pulley and two drive tapes. The pulley diameter is sized to move the inner stage twice the distance of the outer stage. A flexure-based preload adjustment for the drive tape of the outer stage can be adjusted to synchronize (phase) the inner and outer stage motion (Figure 3). The stepper motor works against a preload applied to the inner and outer stages through a symmetric spring system.

In our delay line designs, we seek to simultaneously minimize tilt and lateral run-out and maximize optical path length control bandwidth, precision, and dynamic range. The optical design of the delay line can influence the mechanical and servo design. We are presently focusing on a cat's eye optical design which has the property of turning beam-tilt errors into beam-shear errors. In a cat's eye design, the small secondary mirror is a natural location for fast, small-amplitude optical path length control. Piezo-electric transducers (PZT) actuators have high bandwidth ($\sim$ 1 kHz) but limited range of motion; the range of motion decreases to $\sim$ 25% of the warm value at 4 Kelvin. To compensate for the reduction in PZT range of motion at low temperature, we have developed a momentum compensated, mechanical amplifier ([2]). This device is based on a pair of 4-bar linkages symmetrically driven by the PZT (Figure 4). The 4-bar linkages drive the secondary mirror cell and a proof mass. The angle between the 4-bar linkage segments and the load axis of the PZT determines the theoretical mechanical advantage. With the system we have designed, we expect to recover most of the PZT range of motion.

Our control design is currently based on a two stage servo using a stepper motor for large OPD adjustments and a PZT for fine adjustments. A laser metrology system provides the error signal for closed loop operation. We presently have a PZT with 100 μm of travel (warm) for path length modulation of the cat's eye secondary

Further author information: (Send correspondence to M.S.)
MS: E-mail: swain@huey.jpl.nasa.gov, Telephone: 1 818 354 2871

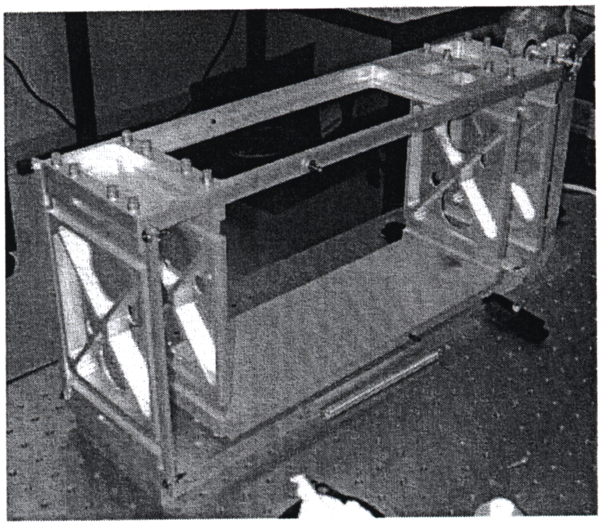

Figure 2.
The flex-blade delay line stage without optics. The lower stage is driven at twice the rate of the upper stage so that there is no net vertical shear with respect to the input beam.

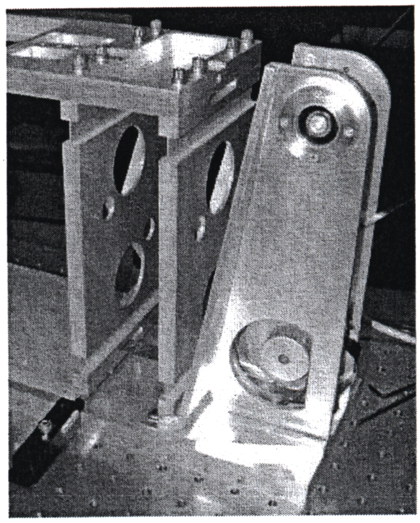

Figure 3.
Detail of the flexure assembly in the flex-blade delay line design. Note the flexure preload termination of the drive strap for the upper stage; adjusting this preload is used to synchronize the motion of the inner and outer stages.

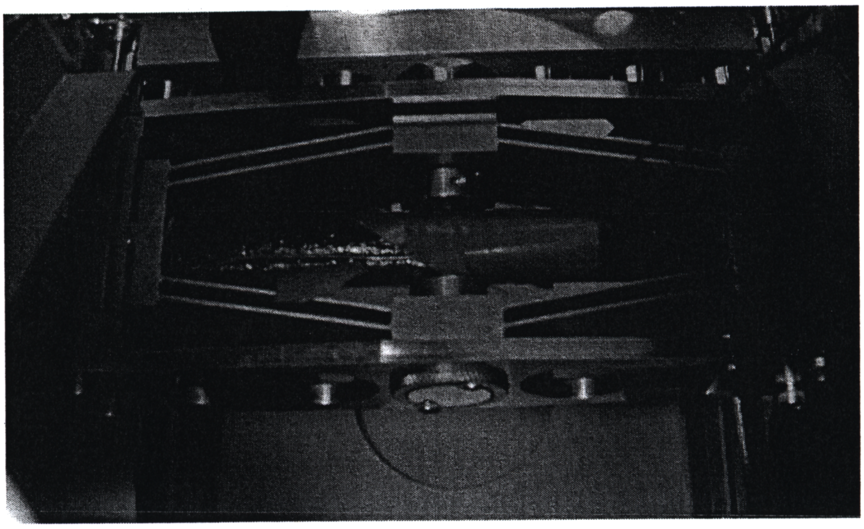

Figure 4.
A top view of the momentum compensated, 4:1, mechanical amplifier. This device is intended to compensate for loss in PZT stroke at cryogenic temperatures. In this configuration, the PZT modulates OPD by adjusting the position of the secondary in a cat's eye optical design for the delay line optics.

mirror; this range of motion for the PZT substantially exceeds the step size of the stepper motor. Because of the relatively large amplitude ($\sim$ few μm), discrete nature of the stepper motor motion, meeting the TPF nulling requirements ($\sim$ 3 nm rms) for optical delay control will be a challenge. We expect to use the PZT to compensate for the step function response of the stepper motor drive. If this two-stage servo approach fails to meet the TPF requirements, we intend to upgrade the delay line to use either an additional servo stage or a different prime mover.

We have tested the first generation strapped-wheel delay line in warm run-out tests, a preliminary cold opearation test, and duration tests. We have tested the first generation flex-blade delay line in warm tests. Warm tests are intended to characterize delay line run-out and tilt as a function of position within the allowable range of motion. We use capacitance sensors in both averaged and differential mode to measure displacement and tilt. We also use an autocollimator to make tilt measurements of a fudicial optic on the stage. Warm run-out tests for the first generation strapped-wheel delay line were reported in and indicated straightness of travel at the $\sim$ 15 μm level for most of the delay line range of motion although run-out at the ends of the range of motion were was worse.

Our preliminary cold test was to operate the first generation strapped-wheel delay line in a fish cooler containing pans with liquid nitrogen. This demonstrated the cryogenic operation of the delay line at 117 K ([2]) but in an environment completely unsuitable for precision measurements. We are presently procuring a large liquid nitrogen dewar for testing of the delay lines at 77 Kelvin. The dewar will provide a thermally and mechanically stable environment for measurement and delay line characterization. Characterization of the mechanical properties of both delay line designs as well as the dynamic range and accuracy of the control system design will be tested at 77 K°.

3. INTEGRATED OPTICS

Our interest in integrated optics for cryogenic space-based interferometers is based on simplifying the instrument alignment process (eliminating control points), making the alignment robust to thermal cycling, and reducing the instrument mass. Given the recent advances in laser micro-machining, it is straight-forward to implement some types of traditional free-space optics functions as conductive wave guide structures ([3]). Our collaboration

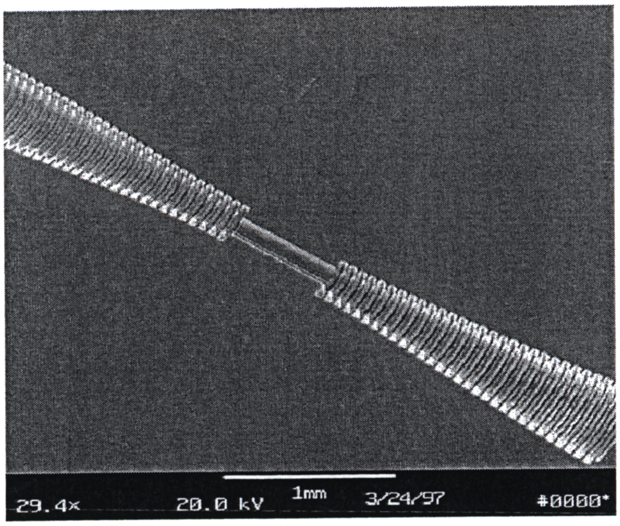

Figure 5. A single mode spatial filter designed for operation at 200 μm.

aims to exploit the micro-machining process under development at the University of Airizona for making spatial filters, power splitters and beam combiners for far-infrared interferometry. Our eventual goal is to make multi-way infrared beam combiners from 10 to 400 μm.

The laser micro-machining process uses a laser to selectively remove material; this process is described in detail in these proceedings ([4]). The machining is performed on a silicon substrate and results in two "halves" of the wave-guide structure. The two halves of the silicon wave-guide structure are then gold coated and mounted together to form the completed device. Because effects from residual surface texture increase as the wavelength decreases, it is easier to make a given structure for longer wavelength operation. Because of the large effective numerical aperture of the wave-guide, horns are needed to couple radiation in and out of the wave-guide structures. We have been making horns and circular wave-guide sections for single-mode spatial filtering (Figures 5 and 6). We have also modeled and fabricate (Figure 7) variety of beam combiner designs for testing in the near future (Figure 8). A pair of back to back feed horns joined by a section of single mode wave-guide designed to operate as a spatial filter at 60 μm will be tested for transmission and spatial mode rejection in the near future.

4. CONCLUSIONS

We are rapidly assembling the constituent pieces, the building blocks, necessary to build and demonstrate a far-infrared, spatial interferometer testbed operating in the 10 to 300 μm range. Our cryogenic delay line concepts are operating warm and will be tested cold as soon as our test dewar is installed and commissioned. The integrated optics for far-infrared spatial interferometry development effort has great potential for simplifying interferometer optical systems. Performance tests of both technologies will occur shortly.

ACKNOWLEDGMENTS

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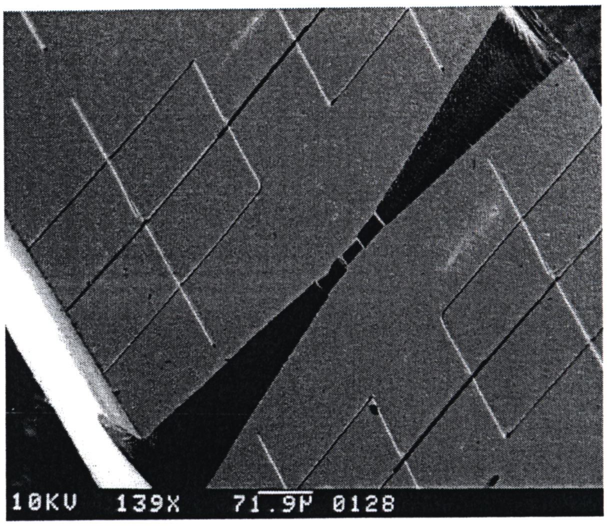

Figure 6. A single mode spatial filter designed for operation at 60 μm.

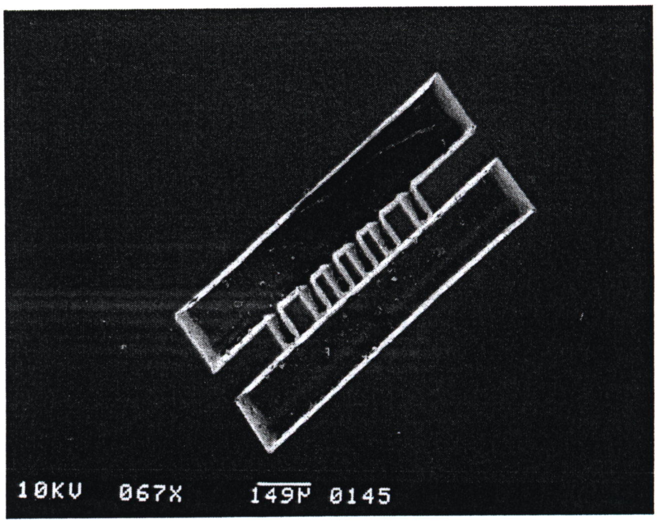

Figure 7. A hybrid coupler power combiner fabrication test.

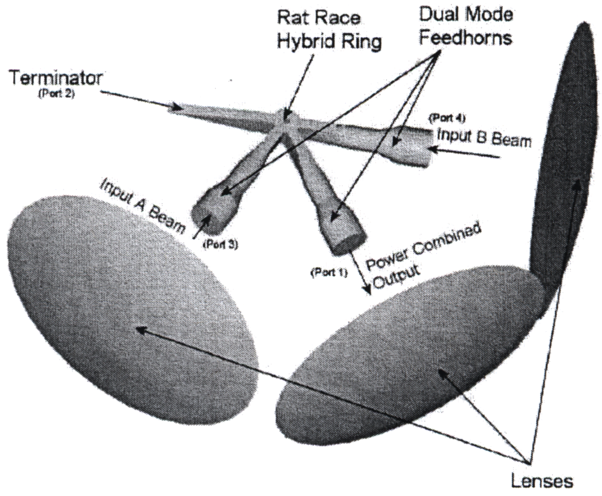

Figure 8.
The "rat race" power combiner design with a lens and horn combination for coupling power in and out of the device.

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